

ANALYSIS OF INDUCTION MOTOR DRIVE WITH DIRECT TORQUE CONTROL SCHEME USING SPACE VECTOR MODULATION

A THESIS SUBMITTED IN PARTIAL FULFILLMENT OF THE
REQUIREMENTS FOR THE DEGREE OF

*Master of Technology
In
Electrical Engineering*

(Power Electronics and Drives)

By

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DEPARTMENT OF ELECTRICAL ENGINEERING

NATIONAL INSTITUTE OF TECHNOLOGY

ROURKELA, ORISSA, INDIA

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ROURKELA

CERTIFICATE

This is to certify that the work in this thesis entitled “**Analysis of Induction Motor Drive with Direct Torque Control scheme using Space Vector Modulation** ” submitted by **Vudatha Vinod Kumar**, to the Electrical Engineering Department, National Institute of Technology, Rourkela, in partial fulfillment of the prerequisites for the award of the degree of “**Master of Technology**” in “*Power Electronics and Drives*” is a bonafide work disbursed by him under my supervision and steerage throughout the academic session 2014-2015.

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Vudatha Vinod Kumar

**DEDICATED TO
MY LOVING
PARENTS**

ABSTRACT

Direct torque control (DTC) is one in all the foremost wonderful management methods of torque control of the induction motor. The aim is to regulate effectively the torque and flux. Torque control of associate induction motor (IM) supported DTC strategy is a developed and a comprehensive study which is made during this project. Direct torque management is that the 1st technology to regulate the important control variables of torque and flux. This methodology makes the rotor more accurate and quick management, high dynamic speed response and easy to regulate. The reference value may be calculated by the flux and torsion estimation and conjointly motor parameters. With the joint progress of numerical electronics and power electronics, it's potential nowadays to subsume the axis management with variable speed in applications involving low power. With these projections of technology, various command approaches are developed by the scientists to master in real time, the torque and also the flux of the electrical ac machines, the direct torque control (DTC) theme being one in all the foremost recent steps during this direction. This theme provides excellent regulation properties without using rotational speed feedback. During this control theme the electro- magnetic torque and mechanical device (stator) flux magnitude are calculable with solely mechanical device voltages and currents and this estimation doesn't rely upon motor parameters apart from the mechanical device (stator) resistance.

In this thesis, typical DTC theme has been delineated. The induction motor (IM) has been simulated in stationary d-q arrangement and its free running acceleration characteristics are drawn. Typical DTC theme has been simulated with a two hundred horse power (200 HP), 460V, 60Hz induction motor. The literature review has been done to review the latest advancements in DTC theme that in someway is ready to beat the drawbacks of the typical one. The space vector modulation technique (SVM) is applied during this project to two level electrical converter (inverter) within the direct torque management primarily based on induction motor drive system. Space vector PWM methodology may be applied as future work to DTC drive system to cut back the torque (torsion) ripple.

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LIST OF SYMBOLS

Subscripts:

a, b, c : for A, B, C phase sequence components respectively s, r : for stator and rotor quantities respectively

q, d : for quadrature and direct axis components

0 : for zero sequence components

l : for leakage quantities

em : for electromagnetic (e.g. T_{em} = electromagnetic torque) sl : for slip quantities

b : for base quantities

m : for magnetizing component

Superscript

s, r : for quantities in stationary and rotor reference frame respectively e : for synchronously rotating reference frame

, (dash) : for referring rotor quantities to stator side

* (star) : for the command values of quantities in simulation model

abc : for matrix notation of any phase quantities

$qd0$: for matrix notation of any $q, d, 0$ quantities

Symbols

IM	Induction motor
IMD	Induction motor drives
ASD	Adjustable speed drives
v	voltage in Volts
i	current in Amperes
z	impedance in Ohms
R	resistance in Ohms
t	time in sec
N	speed in rpm
Φ	flux in Wb
ψ	flux linkage in Volts.sec
L	inductance in Henry
x	reactance in ohms
ω	angular speed in rad/sec
θ	phase angle in rad
	small change
ϕ	phase
T	torque in Nm
P	no of poles
p	differential operator
n	stator to rotor turn ratio

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CHAPTER-1

INTRODUCTION

1.1 Induction motor drives

Over the past years, dc machines were extensively used for variable speed applications as a result of the decoupled management of torsion and flux that will be achieved by armature (coil) and field current management respectively. DC drives has advantages in several facets like starting torque, simple management and nonlinear performance. However as a result of the main demerits of DC machine like the presence of brush assembly and commutator , DC machine drives became disused nowadays in applications in the industry.

The low-cost, robustness, the higher performance and also the simple maintenance build the asynchronous motor advantageous in several industrial applications or general applications. Squirrel cage induction motors (SCIM) are used widely than all the other electrical motors as they all have the benefits of AC motors and are cheaper in price as compared to slip ring Induction motors; need less maintenance and rugged construction. Owing to the slip rings absence, brush maintenance period and price related to the wear and tear and tear of brushes are reduced. As a result of these benefits, the induction motors are the execution part of most of the electrical drive system for all connected aspect such as speed reversal, starting, braking and speed change etc.

To reach the best potency of induction motor drive (IMD), several advanced methods of management has been come up within the previous couple of years. Now-a-days, by utilising fast switching frequency in power converters controlled by microcontrollers, the phase, magnitude and frequency of the input to AC motors will be modified, thus the motor speed and torsion are controlled. Today, it's attainable to contend with the axis control of machine drives with variable speed in low power applications largely as a result of the joint progress of numerical electronics and power electronics. The operation of the induction motor dynamically made the drive system play a vital role on the system performance.

In 1986 **Noguchi and Takahashi** [3] projected a brand new method for the management of three phase IM, quite totally different from field orientating management based on the limit cycle management of each torsion and flux using the optimum PWM output voltage that yields fast torsion response and is extremely economical. Here potency improvement in steady state working performance has been thought of and this projected control circuit has the

demerit of creating the drift in very low frequency operation which might be paid off simply and automatically to minimise the impact of variation of constants of machine.

Thomas G Habetler [4] in **1992** projected a direct torsion management technique of IM (induction machine) which rely on prescient, dead beat control of the torsion and flux. Here the variation in torsion and flux, over entire switching period is computed by assessing the synchronous speed (N_s) and the transient reactance voltage and the voltage of the stator is ascertained that is obliged to bring about the flux and torque to be equivalent to the respective command values. Then space vector pulse width modulation is utilized to characterize switching state of the inverter. To be utilized as a part of the transient or beat dropping mode, an option way to deal with miscreant control is likewise presented.

Vector management of induction motor without using encoder was proposed by **James N Nash** [6] in **1997**. Here a discussion of direct self-control and also the field orientating idea, enforced in adaptive model of motor is bestowed and conjointly the relying of the control technique on quick working methodologies has been stressed.

A new theme of direct torsion management of IM for electric vehicles [10] was projected in **2004** by **M.Vasudevan and Dr. R.Arumugan**, this electric vehicle drive consists of re-wound IM's and a three-level IGBT electrical converter. Field Orientating management, Direct Torsion Control (DTC), and DTC utilizing Space Vector Modulation (SVM) are looked into here and conjointly equivalence between these management methods is bestowed. DTC utilizing Space vector modulation (SVM) is found to be the simplest theme for this use.

A detailed comparison between viable adaptive intelligent torque management ways of Induction motor [11] was bestowed by **M.Vasudevan, R.Arumugan and S.Paramasivam** in **2005** emphasizing its benefits and demerits. The functioning of neural networks, genetic-algorithm and fuzzy based mostly torsion controllers is assessed because of the numerous sensor less DTC methods of induction motor. These reasoning methodologies are given to realize high functioning de-coupled torsion and flux management.

In **2008** **Sarat K Sahoo, Tulsiram Das, Vedam Subrahmanyam** [12] bestowed a straight forward way to deal with style and execution of DTC of 3 stage induction motor utilizing Simulink/Matlab and field programmable gate array software[18]. Two straight forward new methods such as stator-flux assessment and constant switching frequency are projected to keep up this straightforward control structure of direct self control while in the same time rising the execution of the DTC drive. A basic torque control is acquainted with supplant the three level comparators to keep up a steady exchanging recurrence. By utilizing

straight forward method based on final performance, phase error and magnitude related to stator flux assessment based on voltage model is paid off.

A strategy of the variable duty ratio control methodology is proposed by **Prof.K.B.Mohanty in 2009**[15] to expand exchanging recurrence, and change the width of hysteresis-groups of basic DTC according as per the exchanging recurrence. This plan minimizes torsion and current ripples, improves torsion response, and diminish the exchanging losses being its straightforwardness.

Direct torque management of induction motor using SVPWM technique was described by **S.L.Kaila and H.B.Jani in 2011**. The exchanging time bounds of various space vectors are found for each sampling period in the way to lessen the torsion ripple in space vector PWM method.

1.2 Types of control schemes

There are two important steps to design a control system for electrical drives

1. In order to accomplish the analysis and the evaluation of the system, first the drive system need to modelled mathematically.
2. When external perturbations are present, through an optimal regulator the imposed response on the system is obtained.

There are two fundamental directions of IM control [1]

- **Analogue:** direct measurement of the machine parameters (mainly the rotor speed), which are compared to the reference signals through closed control loops.
- **Digital:** calculation of the machine parameter values in the sensorless control schemes (without measuring the rotor speed).

The parameter estimation can be done by implementing following methodologies [1]

- Slip frequency calculation method
- Speed estimation using state equation;
- Estimation based on slot-space harmonic voltage;
- Flux vector control and flux estimation;
- Direct control of torque and flux;
- Observer-based sensorless speed control;
- Model reference adaptive systems;
- Techniques of kalman filtering;

- Parameter adaptation sensorless control;
- Sensorless control based on neural network;
- Sensorless control based on fuzzy-logic.

Classification of control techniques for IM from the view point of the controlled signal [1][2]:

- **Scalar control:** Based on the relationships valid in the steady state, only magnitude and frequency of current, voltage and flux linkage space vectors are controlled. Disregards the coupling effect in the machine.
- **Vector control:** based on relations valid in dynamics state, not only magnitude and frequency but also an instantaneous position of voltage, flux linkage space vector and current are controlled. The most popular vector control methods are the Field oriented control (FOC) and DTC.

Scalar controlled drives gives somewhat low performance, but easy to implement. Their importance has been diminished recently because of the superior performance of vector controlled drives which are demanded in many applications [5].

1.3 Direct torque control

DTC was first introduced by Takahashi in 1984 in Japan and by Dopenbrock in 1985 in Germany [3] [7] and today this control scheme is considered as the world's most advanced AC Drives control technology. This is a simple control technique which does not require coordinate transformation, PI regulators, and Pulse width modulator and position encoders [20] [25]. This technique results in direct and independent control of motor torque and flux by selecting optimum inverter switching modes. The electromagnetic torque and stator flux are calculated from the primary motor inputs e.g. stator voltages and currents [16]. The optimum voltage vector selection for the inverter is made so as to restrict the torque and flux errors within the hysteresis bands. The advantages of this control technique are quick torque response in transient operation and improvement in the steady state efficiency.

1.4 MOTIVATION

The electric drives used in industry are Adjustable Speed Drives and in most of these drives AC motors are used. Induction motors are the best in these drives. Induction motors are today the most widely used ac machines due to the advantageous of low cost, reliability and performance. So effective control of IM parameters e.g. speed, torque and flux is of utmost importance. From the investigation of the control methods, it is known that torque control of IM could be accomplished according to various techniques ranging from inexpensive Volts/Hz ratio strategy to sophisticated sensorless vector control method. But every scheme has its disadvantages like losses, the need of separate current control loop, coordinate transformation (thus increasing the complexity of the controller), current ripple and torque etc. So it is very much essential to design a controller to obtain an ideal electric vehicle motor drive system that would have high efficiency, low torque ripple and minimum current distortion.

1.5 OBJECTIVE

The primary aim of this project work is to develop;

1. a control method in order to achieve fast torque response, superior dynamic response.
2. a controller bearing low inverter switching frequency, less harmonic losses, high efficiency. The direct torque controller has all those features to be a best controller. So the aim here is to analyse the most sophisticated IM control method i.e. DTC and investigate its performance characteristics.

1.6 OVERVIEW OF THE THESIS

Chapter 2: Mathematical modelling of three phase IM is discussed, reference frames idea and the dynamic equations of the IM in several reference frames, stationary reference frame equations are to be employed in coming chapters. A brief description of voltage source inverter is also given in this chapter. A Simulink model of the induction motor in the stationary reference frame is given.

Chapter 3: Basic direct torque control DTC methodology is discussed, discusses principle of DTC and several techniques of assessing stator flux in detail, a brief description about the hysteresis comparators is made.

Chapter 4: Basic direct torque control technique is simulated by SIMULINK/MATLAB. The scheme is run for applied values of torque and command speed conditions. Initially, the starting transient of DTC drive for no load condition is observed and later performance of the machine for speed reversal is checked. Flux plot of DTC drive is also shown.

Chapter 5: gives summary of complete work, inferences and the scope for future work.

CHAPTER 2

VOLTAGE SOURCE INVERTER FED INDUCTION MOTOR DRIVES

2.1 Introduction

The type of waveforms that the electric drive system deals with is ac waveforms, so the main objective of power converters needed in adjustable speed drives (ASDs) should produce an ac output waveform from a dc power supply. The magnitude, frequency, and phase of the sinusoidal ac outputs should be controllable. Based on the type of ac output waveform, the power converter topologies can be considered as voltage source inverters (VSIs) and current source inverters (CSIs). The voltage source inverters, where the ac output voltage waveform can be controlled independently, is the most widely used power converters in ASDs and many industrial applications because they naturally behave as voltage sources as required in these applications. The VSI output is given to the three phase induction motor which is finally connected to the drive system load.

2.2 Induction motor dynamic model

The induction motor stator consists of three phase balanced distributed windings with each phase classified from other two windings by 120 degrees in space [1]. When current flows through these windings, three phase rotating magnetic field is produced. The dynamic behaviour of the induction machine is taken into account in an adjustable speed drive system using a power electronics converter. This machine constitutes an element within a feedback loop. Study of the dynamic performance of the machine is unpredictable due to coupling effect of the rotor and stator windings; also the coupling coefficient varies with rotor position. So a set of differential equations with time-varying coefficients describe the machine model [1].

To derive the dynamic model of the machine, the following assumptions are made:

- No magnetic saturation;
- No saliency effects i.e. machine inductance is independent of rotor position;
- Stator windings are so arranged as to produce mmf distribution which is sinusoidal;
- Stator slots effect may be omitted;
- No fringing of the magnetic circuit;
- Constant intensity of magnetic field, directed towards the air-gap radially;

- Negligible hysteresis and eddy currents

A balanced three phase supply is given to the motor from the power converter. For dynamic modelling of the motor, two axes theory is used [1]. The theory suggests that the parameters which are time varying can be expressed in mutually perpendicular quadrature (q) and direct (d) axis. For the representation of the d - q dynamic model of the machine a stationary or rotating reference frame is assumed.

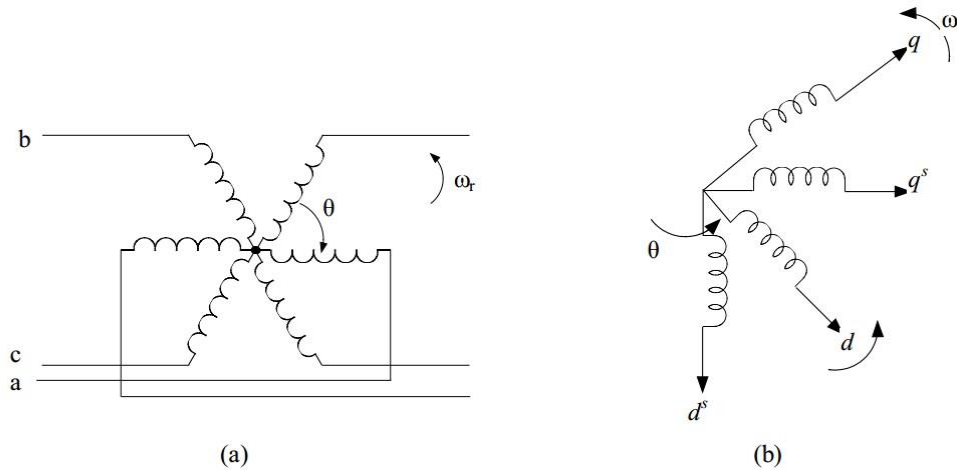


Fig.2. 1 (a) Rotor and stator winding coupling of motor (b) Machine 2 phase equivalent

In stationary reference frame, the d^s and q^s axes are fixed on the stator, whereas these are rotating at an angle with respect to the rotor in rotating reference frame. The rotating reference frame either may be fixed on the rotor or it may be rotating at synchronous speed. In synchronously rotating reference frame with sinusoidal supply the machine variables seem as quantities in dc in steady state condition [24].

2.2.1 Axes transformation

(a) Transformation from 3 phase to 2 phase :

A 3 phase symmetrical machine is deliberated with stationary as - bs - cs axes at 120° difference as shown in fig.2.2.

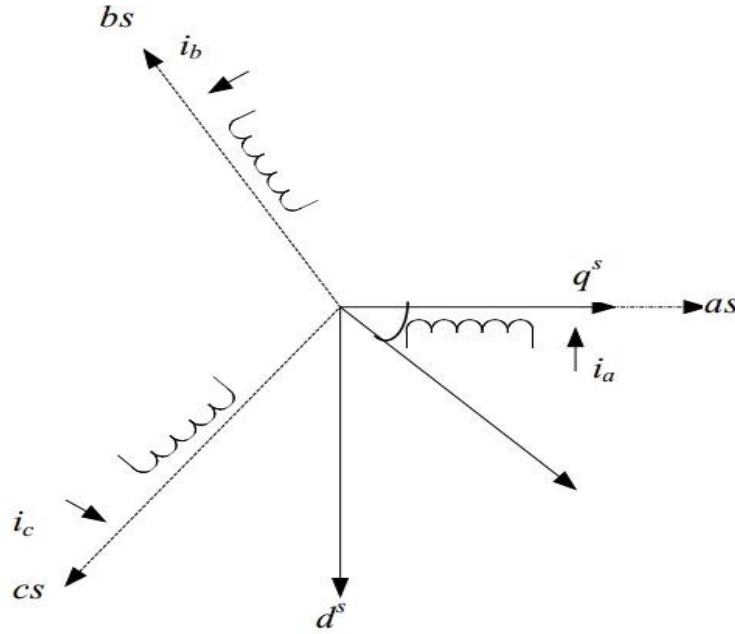


Fig.2.2 Axis transformation from as - bs - cs to d^s - q^s

The voltages v_{as} , v_{bs} , v_{cs} are the voltages of as , bs , cs phases consecutively. Now assuming that the d^s - q^s stationary axes are tailored at angle θ as shown and the voltages across d^s - q^s axes to be v_{ds}^s , v_{qs}^s consecutively, the two phase stationary voltages can be transformed to 3 phase voltages based on math equations as follows:

$$v_{as} = v_{qs}^s \cos \theta + v_{ds}^s \sin \theta \quad (2.1)$$

$$v_{bs} = v_{qs}^s \cos(\theta - 120^\circ) + v_{ds}^s \sin(\theta - 120^\circ) \quad (2.2)$$

$$v_{cs} = v_{qs}^s \cos(\theta + 120^\circ) + v_{ds}^s \sin(\theta + 120^\circ) \quad (2.3)$$

The phase voltages in matrix form can be written as:

$$\begin{bmatrix} v_{as} \\ v_{bs} \\ v_{cs} \end{bmatrix} = \begin{bmatrix} \cos \theta & \sin \theta & 1 \\ \cos(\theta - 120^\circ) & \sin(\theta - 120^\circ) & 1 \\ \cos(\theta + 120^\circ) & \sin(\theta + 120^\circ) & 1 \end{bmatrix} \begin{bmatrix} v_{qs}^s \\ v_{ds}^s \\ v_{0s}^s \end{bmatrix}$$

By inverse transformation, v_{ds}^s and v_{qs}^s can be written in terms of three phase voltages in matrix form as follows:

$$\begin{bmatrix} v_{qs}^s \\ v_{ds}^s \\ v_{0s}^s \end{bmatrix} = \frac{2}{3} \begin{bmatrix} \cos \theta & \cos(\theta - 120^\circ) & \cos(\theta + 120^\circ) \\ \sin \theta & \sin(\theta - 120^\circ) & \sin(\theta + 120^\circ) \\ 0.5 & 0.5 & 0.5 \end{bmatrix} \begin{bmatrix} v_{as} \\ v_{bs} \\ v_{cs} \end{bmatrix}$$

Where v_{0s} = zero sequence component which may or may not present.

For convenient q^s axis is aligned with the as -axis i.e. $\theta = 0$ and zero sequence component is neglected. So the transformation relations are reduced to

$$v_{as} = v_{qs}^s \quad (2.4)$$

$$v_{bs} = -\frac{1}{2}v_{qs}^s - \frac{\sqrt{3}}{2}v_{ds}^s \quad (2.5)$$

$$v_{cs} = -\frac{1}{2}v_{qs}^s + \frac{\sqrt{3}}{2}v_{ds}^s \quad (2.6)$$

$$v_{qs}^s = v_{as} \quad (2.7)$$

$$v_{ds}^s = -\frac{1}{\sqrt{3}}(v_{bs} - v_{cs}) \quad (2.8)$$

(b) Transformation from 2 phase stationary to 2 phase synchronous rotating frame of reference:

The d^s - q^s stationary axes are translated to d^e - q^e synchronous rotating frame of reference that is moving with speed ω_e w.r.t axes d^s - q^s by the use of fig.2.3.

The angle difference between axes d^s and d^e is $\theta_e = \omega_e t$. The voltages v_{ds}^s , v_{qs}^s can be transformed to voltages on axis d^e - q^e based on the below equations:

$$v_{ds} = v_{qs}^s \cos \theta_e - v_{ds}^s \sin \theta_e \quad (2.9)$$

$$v_{qs} = v_{qs}^s \sin \theta_e + v_{ds}^s \cos \theta_e \quad (2.10)$$

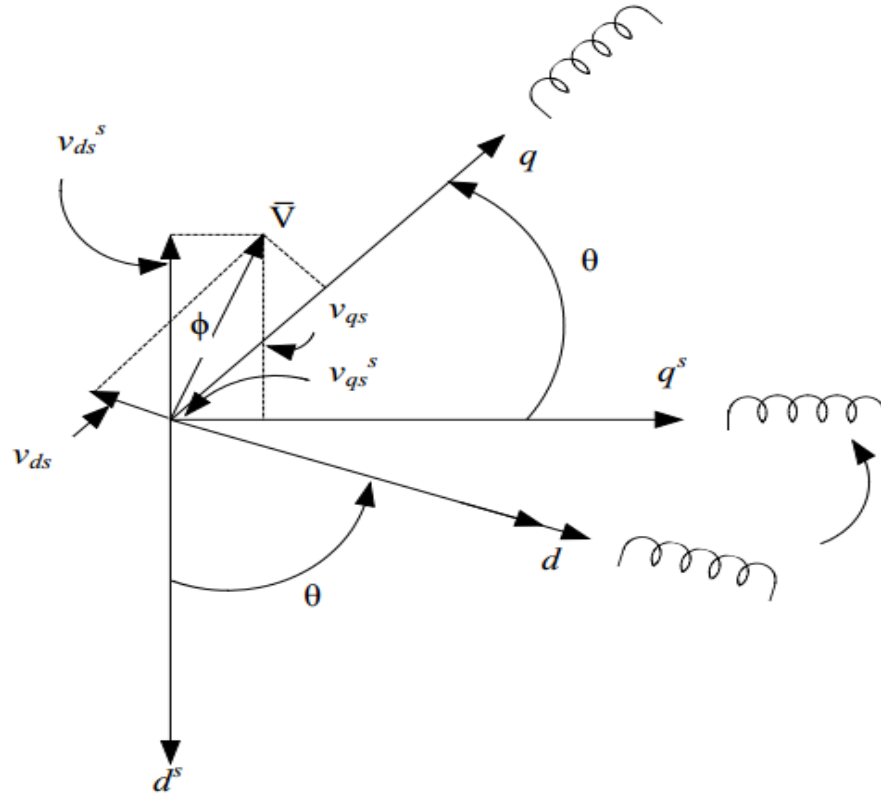


Fig.2. 3 Transformation from stationary d - q frame to synchronous rotating frame

The rotating frame arguments to stationary frame transformation is concurring to the below equations:

$$v_{qs}^s = v_{qs} \cos \theta_e + v_{ds} \sin \theta_e \quad (2.11)$$

$$v_{ds}^s = -v_{qs} \sin \theta_e + v_{ds} \cos \theta_e \quad (2.12)$$

Presuming that the 3-phase voltages are sinusoidal and balanced given by following

$$v_{as} = V_m \cos(\omega_e t + \phi) \quad (2.13)$$

$$v_{bs} = V_m \cos(\omega_e t + \phi - 2\pi/3) \quad (2.14)$$

$$v_{cs} = V_m \cos(\omega_e t + \phi + 2\pi/3) \quad (2.15)$$

Replacing equations (2.13) – (2.15) in equations (2.8) and (2.9) we yield

$$v_{qs}^s = V_m \cos(\omega_e t + \phi) \quad (2.16)$$

$$v_{ds}^s = -V_m \sin(\omega_e t + \phi) \quad (2.17)$$

Replacing (2.16) – (2.17) in (2.9) – (2.10)

$$v_{qs} = V_m \cos \phi \quad (2.18)$$

$$v_{ds} = -V_m \sin(\phi) \quad (2.19)$$

From math equations (2.18) and (2.19) it is understood that sinusoidal quantities in the stationary reference frame come out as quantities in dc in the synchronously rotating frame of reference.

2.2.2 Stationary frame Motor dynamic model:

Stationary frame model of machine by Stanley equations replacing $\omega_e = 0$.
Equations of the circuit of stator are written as:

$$v_{qs}^s = R_s i_{qs}^s + \frac{d}{dt} \psi_{qs}^s \quad (2.20)$$

$$v_{ds}^s = R_s i_{ds}^s + \frac{d}{dt} \psi_{ds}^s \quad (2.21)$$

$$0 = R_r i_{qr}^s + \frac{d}{dt} \psi_{qr}^s - \omega_r \psi_{dr}^s \quad (2.22)$$

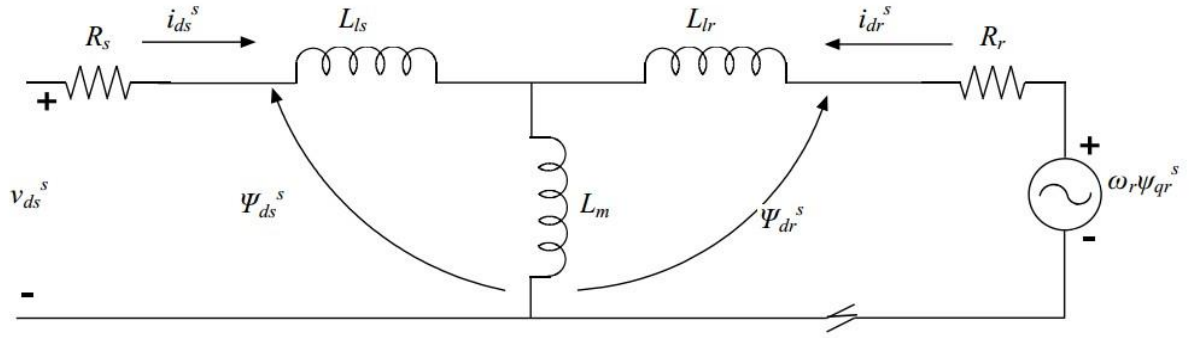
$$0 = R_r i_{dr}^s + \frac{d}{dt} \psi_{dr}^s + \omega_r \psi_{qr}^s \quad (2.23)$$

Where ψ_{ds}^s ψ_{qs}^s d-axis and q-axis flux linkages of stator

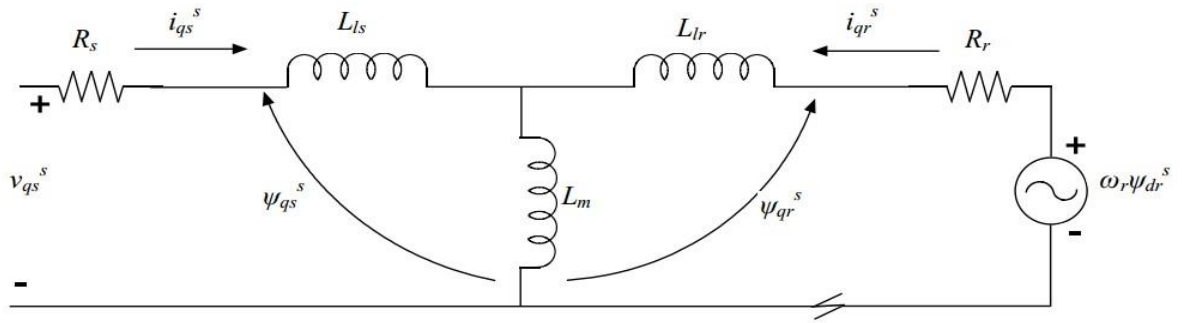
ψ_{qr}^s, ψ_{dr}^s = q-axis and d-axis rotor flux linkages

R_s, R_r = stator and rotor resistances

ω_r = rotor speed and $v_{dr} = v_{qr} = 0$



(a)



(b)

Fig.2.4 Equivalent circuits of d^s - q^s

The electromagnetic(Tem) torque is produced by the fundamental interaction of rotor mmf & air gap flux which is shown in normal vector form as

$$T_e = \frac{3P}{2} (\bar{\psi}_m) * (\bar{I}_r)$$

The equations of torque can be written in stationary reference frame with relating quantities as

$$T_e = \frac{3P}{2} (\psi_{dm}^s i_{qr}^s - \psi_{qm}^s i_{dr}^s) \quad (2.24)$$

$$= \frac{3P}{2} (\psi_{dm}^s i_{qs}^s - \psi_{qm}^s i_{ds}^s) \quad (2.25)$$

$$= \frac{3P}{2} (\psi_{ds}^s i_{qs}^s - \psi_{qs}^s i_{ds}^s) \quad (2.26)$$

$$= \frac{3P}{2} L_m (i_{dr}^s i_{qs}^s - i_{qr}^s i_{ds}^s) \quad (2.27)$$

$$= \frac{3P}{2} (\psi_{dr}^s i_{qr}^s - \psi_{qr}^s i_{dr}^s) \quad (2.28)$$

2.3 Voltage source inverter

In VSIs the input voltage is maintained constant and the amplitude of the output voltage is independent of the nature of the load. But the output current waveform as well as magnitude depends upon nature of load impedance. Three phase VSIs are more common for providing adjustable frequency power to industrial applications as compared to single phase inverters. The VSIs take dc supply from a battery or more usually from a 3- ϕ bridge rectifier.

A basic three phase VSI is a six step bridge inverter, consisting of minimum six power electronics switches (i.e. IGBTs, Thyristors) and six feedback diodes. A step can be defined as the change in firing from one switch to the next switch in proper sequence. For a six step inverter each step is of 60° interval for one cycle of 360° . That means the switches would be gated at regular intervals of 60° in proper sequence to get a three phase ac output voltage at the output terminal of VSI. Fig.2.5 shows the power circuit diagram of three phase VSI using six IGBTs and six diodes connected anti parallel to the IGBTs. The capacitor connected in to the input terminals is to maintain the input dc voltage constant and this also suppresses the harmonics fed back to the dc source. Three phase load is star connected.

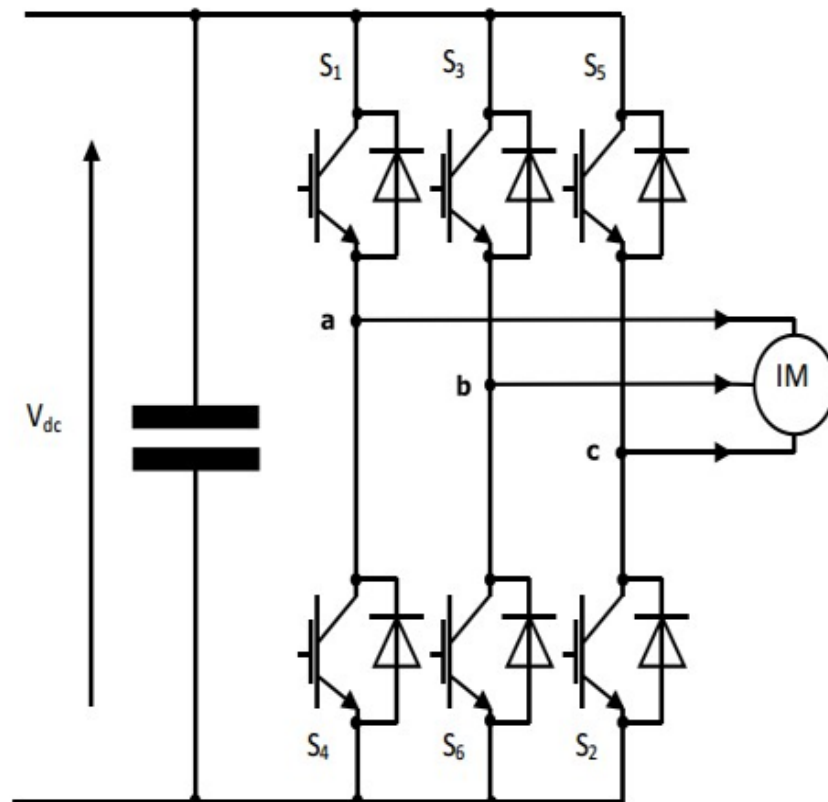


Fig 2.5 Three Phase VSI using IGBT'S

The six switches are divided into two groups; upper three switches as positive group (i.e. S_1 , S_3 , S_5) and lower three as negative group of switches (i.e. S_4 , S_6 , S_2). There are two possible gating patterns to the switches i.e. there are two conduction modes: 1. 180° conduction mode and 2. 120° conduction mode. In each pattern the gating signals are applied and removed at an interval of 60° of the output voltage waveform. In 180° mode three switches are on at a time, two from positive group and one from negative group or vice versa, each switch conducts for 180° of a cycle. In 120° mode each switch conduct for 120° in one cycle and two switches remain turned on at a time, one from positive group and one from negative group. But no two switches of the same leg should be turned on simultaneously in both cases as this condition would short circuit the dc source.

In 120° conduction mode the chances of short circuit of the dc link voltage source is avoided as each switch conduct for 120° in one cycle, so there is an interval of 60° in each cycle when no switch is in conduction mode and the output voltage at this time interval is zero. In general there is a 60° interval between turning off one switch and turning on of the complimentary switch in the same leg. This 60° interval is sufficient for the outgoing switch to regain its forward blocking capability.

The standard three-phase VSI topology has eight valid switching states which are given in Table. 1. Of the eight valid switching states, two are zero voltage states (0 and 7 in Table.1) which produce zero ac line voltages and in this case, either through the upper or lower components, the ac currents free wheel. The remaining states (1 to 6 in Table .1) are active states which produce non-zero ac output voltages. The inverter switches from one state to another in order to generate a given voltage waveform. Thus the ensuing ac output line voltages consist of discrete values of voltage for the topology shown in the figure 2.5. In 180° degree mode of conduction, the waveform of ac phase output voltage is stepped one and line voltage waveform is quasi square wave.

Table 2.1 Switching states of a three phase VSI

State	S_a	S_b	S_c	Vector
0	0	0	0	V_0
1	1	0	0	V_1
2	1	1	0	V_2
3	0	1	0	V_3
4	0	1	1	V_4
5	0	0	1	V_5
6	1	0	1	V_6
7	1	1	1	V_7

2.4 Conclusion

In this chapter IM detailed dynamic model is discoursed in stationary reference frame. In objective to design and understand vector controlled drives the machine dynamic model to be commanded should be understood which would be a good assessment of the true model. For the formulation of the model space phasor notations and two axis theory has been utilized. It is proved that notation of space phasor is easier and compact to deal with.

CHAPTER-3

INDUCTION MOTOR - DIRECT TORQUE CONTROL

3.1 Introduction

In the last decade “induction motor control techniques” have been the field of involvement of so many scientists to put out distinctive answers for control of induction motor having highlights of fast and precise torque response, and decrease in the multifaceted nature of field orientating control [3]-[7]. The DTC procedure has been perceived as the basic and practical answer to accomplish this needs. DTC is a standout among the most incredible and productive control techniques of IM. This strategy is in view of decoupled control of stator flux and torque and as of now it is a standout amongst most effectively researched methods where the objective is to control perfectly the flux and torque.

3.1.1 DTC scheme- Conventional

The traditional DTC scheme is a closed loop assure scheme, the vital components of the command structure being: the circuit of power supply, a 3 stage VSI, the IM, the pace controller to obtain the torque reference and the direct torque controller. The direct torque controller again comprises of flux and torque assessment block, 2 hysteresis torque and flux controllers and sector selection logic block, the outcome of the direct torque controller is the inverter gating pulses.

The direct torque plan does not oblige axes change as all the controlling methods are completed in stationary reference frame. So this scheme does not experience the ill effects of parameter changes to the way that different control methods do. Likewise there is no feedback control loop of current because of which the control activities don't experience the inherent defers in the present regulators, no PWM'S, no regulators of PI, and no rotor position or speed sensor. So it is a sensorless regulatory method which works the machine free from obliging a shaft hopped on mechanical detector. Here on-line flux and torsion calculators are utilized for loop closing. Here the stator flux and torsion are controlled specifically by utilizing hysteresis controllers. In Fig. 3.1 the essential fundamental figure of traditional DTC plan [8] [10] is shown.

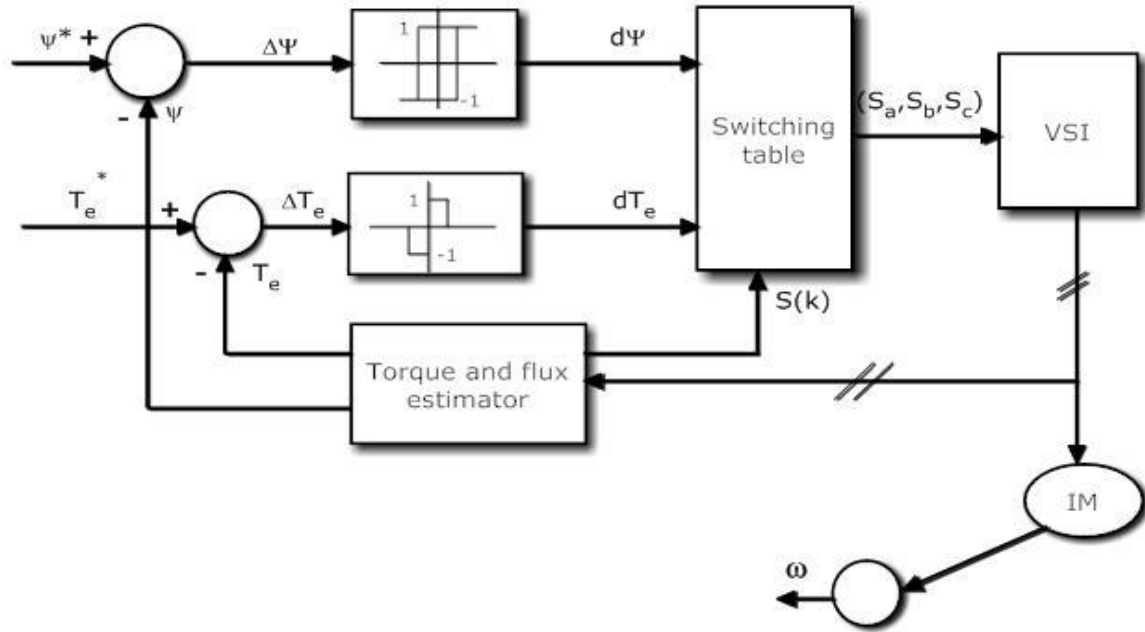


Fig.3. 1 Block diagram of conventional DTC scheme for IM drives

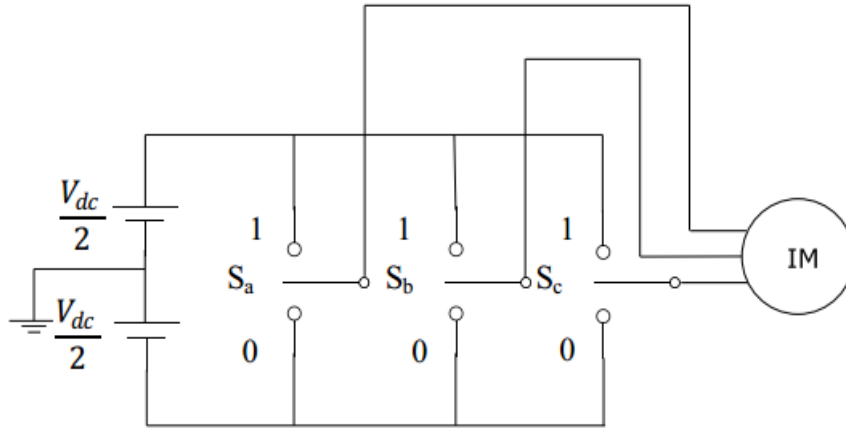
3.2 DTC scheme - Principle

The standard principle of direct torque control is to choose specifically the voltage vectors of stator as per the flux and torsion errors which are the contrasts from the command values of stator flux linkage and torque and their real values. The overseeing math equation for torsion for this plan is because of the interaction of rotor and stator field. Torsion and stator flux linkage are calculated from measured motor terminal quantities i.e current and stator voltages. An ideal voltage vector for the switching of inverter is chosen from the six active voltage vectors and two zero voltage vectors by the hysteresis control of torque and flux of stator.

As we probably aware from the past chapter that a 3-stage VSI has eight conceiving combinings of six switches that is demonstrated in fig.3. 2. The six igbt's have an all around characerized state: ON or OFF in every arrangement. So all the possible arrangements can be related with three bits (S_a, S_b, S_c), one for every inverter leg [17]. The bit is made to 1 if the upper switch is on and to 0 when the lower switch is on. With a specific end goal to avoid supply short circuit, the mode of the top switch is constantly inverse to that of the bottom switch.

The stator voltage space vector is

$$\bar{V}_s = \frac{2}{3} E (S_a + e^{j\frac{2\pi}{3}} S_b + e^{j\frac{4\pi}{3}} S_c)$$

Fig3.2 Simplified 3- ϕ VSI

3.2.1 Direct flux control

In stationary frame of reference outline the stator flux mathematical equation can be composed as:

$$\bar{\Psi}_s = \int (\bar{v}_s - \bar{i}_s R_s) dt \quad (3.2)$$

In case the resistance drop of stator is disregarded for straightforwardness, the stator flux differs with the direction of connected voltage vector and the comparison will be deducted to

$$\Delta \bar{\Psi}_s = \bar{V}_s \Delta t \quad (3.3)$$

Which implies, by applying voltage vector of stator \bar{V}_s for a period increase Δt , $\bar{\Psi}_s$ can be varied additively. The reference value of the vector of stator flux $\bar{\Psi}_s^*$ takes after a round about trajectory, the plane of flux of stator is separated into six sectors as shown. Each sector has an alternative arrangement of voltage vector to raise or diminish the stator flux. The reference flux vector turns in anticlockwise course in a trajectory path and the real stator flux vector $\bar{\Psi}_s$ chases the reference flux in a crisscross way yet compelled to the hysteresis band which is indicated in fig.3.3.

When all is said is done the dynamic forward vectors ($V_{s,k+1}$ and $V_{s,k+2}$) are connected to raise or diminish the stator flux separately whenever the stator flux is in sector k . The radial (outspread) vectors of voltage ($V_{s,k}$ and $V_{s,k+3}$) which rapidly influence the flux are by and large evaded. The dynamic converse vectors of voltage ($V_{s,k-1}$ and $V_{s,k-2}$) are utilized to raise or diminish the stator flux backward heading. The stator flux vector vary because of stator voltage vector is speedy though change in rotor flux is slow due of its huge time constant T_r . This is the reason $\bar{\Psi}_s$ movement is shaky and $\bar{\Psi}_r$ moves consistently at frequency ω_e as that is more seperated. Moreover the normal rate of both continuous as before in final condition.

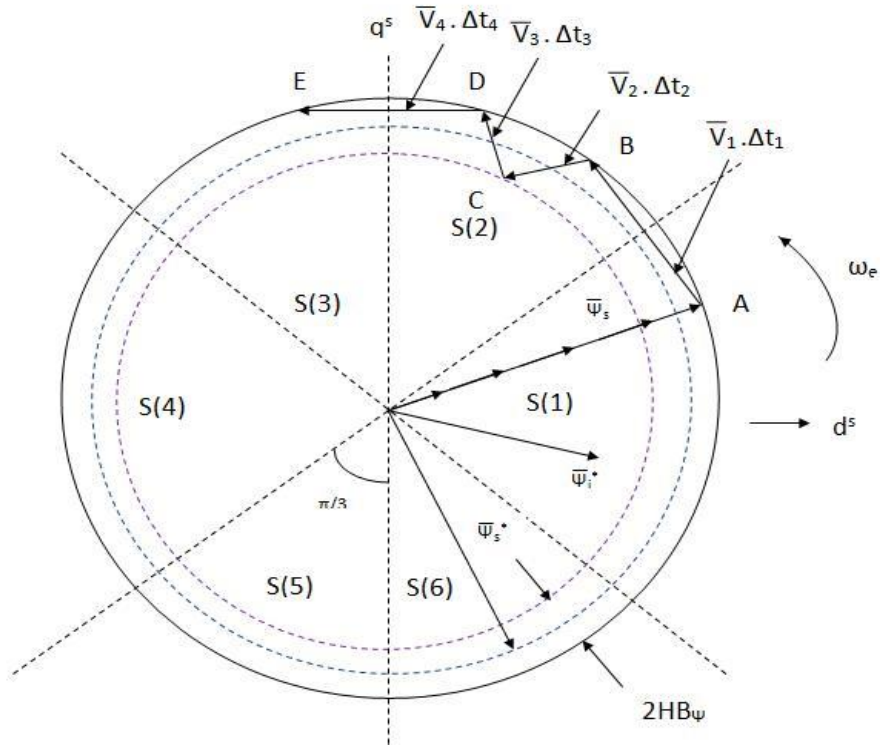


Fig. 3.3 Circular trajectory of stator flux

3.2.2 Direct torque control

The electromagnetic torque (T_e) produced because of interaction of rotor flux and stator flux is suggested by the below equation:

$$T_e = \frac{3}{2} \left(\frac{P}{2} \right) \frac{L_m}{L'_s L_r} \bar{\Psi}_s^* \bar{\Psi}_r = \frac{3}{2} \left(\frac{P}{2} \right) \frac{L_m}{L'_s L_r} \Psi_s \Psi_r \sin \gamma \quad (3.4)$$

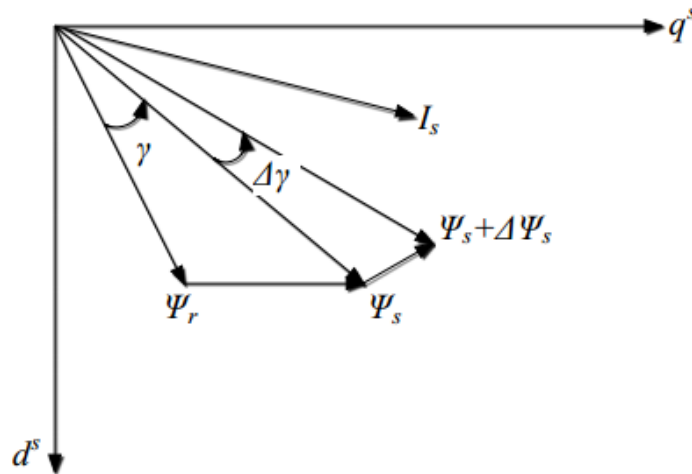


Fig. 3.4 Rotor flux, stator flux and stator current vectors in reference plane d^s - q^s

From the above it is clear that torque changes proportionately as angle between rotor flux and stator flux i.e. γ . To get high dynamic execution it is obliged to shift γ rapidly. Expecting the rotor is moving in anticlockwise direction constantly and flux vector of stator lies in sector k , the dynamic voltage vectors ($V_{s,k+1}$ and $V_{s,k+2}$) are connected to increment γ so as the torque T_e . The outspread voltage vectors ($V_{s,k}$ and $V_{s,k+3}$) are utilized to abatement γ and T_e . By employing the dynamic converse voltage vectors ($V_{s,k-1}$ and $V_{s,k-2}$) torsion could be diminished quickly. The 2 zero voltage vectors ($V_{s,0}$ and $V_{s,7}$) are connected to keep up the flux consistent perfectly and to diminish the torsion somewhat.

3.2.3 Switching Choice

An elite torque control can be built up because of the decoupled regulation of stator flux and torque in direct torque control. Fig.3.5 demonstrates an illustration of flux of stator situated in sector-1 with relating optimum switching voltage vectors for anti-clockwise and it's vice-versa revolution of the shaft.

Optimum selection of switching vector table given by table blow demonstrates the optimum choice of the switching vectors in all arcs of the plane of stator flux. This table is in view of the estimation of error status of flux and torsion & counter-clockwise rotation of the shaft orientation of stator flux [8].

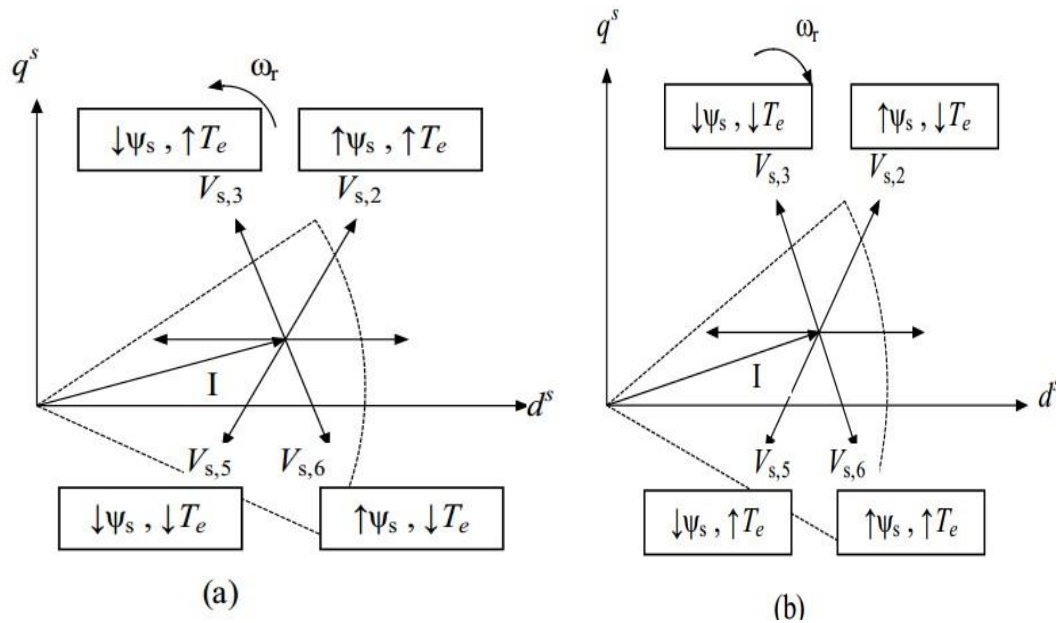


Fig.3. 5 Voltage vecto- switching choice in sector-one for (a) anti-clockwise and (b) clockwise revolution

Table 3.1: Applied selected voltage vectors

Hψ	HTe	S(1)	S(2)	S(3)	S(4)	S(5)	S(6)
1	1	V ₂	V ₃	V ₄	V ₅	V ₆	V ₁
	0	V ₇	V ₀	V ₇	V ₀	V ₇	V ₀
	-1	V ₆	V ₁	V ₂	V ₃	V ₄	V ₅
-1	1	V ₃	V ₄	V ₅	V ₆	V ₁	V ₂
	0	V ₀	V ₇	V ₀	V ₇	V ₀	V ₇
	-1	V ₅	V ₆	V ₁	V ₂	V ₃	V ₄

3.3 Estimation of stator flux

For precise computation of torque and stator flux misplays, an exact assessment of stator flux is vital. There are normally utilized strategies of calculation of flux, in particular models of stator voltage and current.

3.3.1 Stator voltage model

This is the least complex system for stator flux assessment, where the system terminal currents and voltages are detected and from the stationary reference frame comparable circuit the fluxes are processed. The assessed stator flux is produced by accompanying math-statement:

$$\psi_{ds}^s = \int (v_{ds}^s - i_{ds}^s R_s) dt \quad (3.5)$$

$$\psi_{qs}^s = \int (v_{qs}^s - i_{qs}^s R_s) dt \quad (3.6)$$

$$\psi_s = \sqrt{\psi_{ds}^{s2} + \psi_{qs}^{s2}} \quad (3.7)$$

This technique gives exact flux estimation at high speed yet in applications in industries obliging vector drives start-up at zero. This strategy cannot be utilized because at low speed stator resistance drop gets to be noteworthy bringing on wrong estimation. Likewise at low frequency, voltage signs are low and dc offset has a tendency to make up at the output while integration, thus perfect integration gets to be troublesome.

3.3.2 Current model

In stationary frame reference outline, current model is all round stable and the drives functioning could be reached out down to zero speed. Anyhow this model is much unpredictable when contrasted with voltage display as here the learning of rotor speed and

current of stator is obliged to assess rotor flux and stator flux could be evaluated in light of the assessment of flux linkage of rotor. The dynamic mathematical statements of IM in stationary frame of reference, rotor and stator flux can be derived which are furnished below:

$$\frac{d}{dt}\bar{\psi}_r = ((L_m i_s - \bar{\psi}_r)/T_r) - \omega_r \bar{\psi}_r \quad (3.8)$$

$$\bar{\psi}_s = \frac{L_m}{L_r} \bar{\psi}_r + \sigma L_s i_s \quad (3.9)$$

Here the math include closed loop integration, so there is no issue of drift in integration in current model at less speed locale. Moreover assessment exactness is influenced because of parameter variation of motor, especially rotor resistance variation gets to be predominant by temperature and skin effect.

It is perfect to have a hybrid model in light of the remarkable highlights picked up by both frameworks individually where the model of voltage would be successfull at more speed extent and model of current at less speed extent.

3.4 Hysteresis controller

Direct torque control of induction motor drives obliges two hysteresis regulators. The drive execution is impacted by the width of the groups of hysteresis regarding flux and torsion ripples, harmonics in current and the frequency of switching devices of power electronics. Current variation is diminished by small flux hysteresis band and torsion ripple is decreased by small torque hysteresis regulators. In every sampling time, the inverter switching state is overhauled. The state of inverter stays constant, until the result conditions of the hysteresis regulator alter within a sampling time. If the band of hysteresis is fixed, the frequency of switching absolutely relies up on the rate of progress of flux and torsion.

3.4.1 Torque hysteresis controller

The Torque hysteresis regulator is a 3 level controller. It implies the torsion control loop has 3 levels of digital yields. The torsion error ΔT_e is applied to the torque hysteresis regulator and the yield is torque slip status (dT_e) that have 3 values -1, 0 or 1. The width of the hysteresis regulator is $2\Delta T_e$. The error status of torsion is supplied to the exchanging table for voltage vector optimum choosing for the inverter.

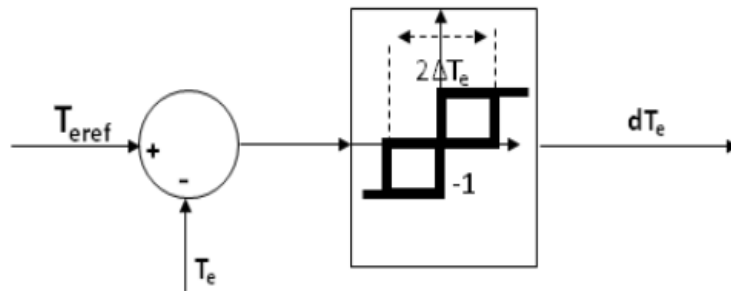


Fig.3. 6 (a) Torque hysteresis controller

Torque error $\Delta T_e = T_{\text{ref}} - T_e$

$|dT_e| = 1$ if $|T_e| < |T_{\text{ref}}| - |\Delta T_e|$: Torque should be increased

$|dT_e| = -1$ if $|T_e| > |T_{\text{ref}}| + |\Delta T_e|$: Torque should be decreased

$|dT_e| = 0$ if $|T_{\text{ref}}| - |\Delta T_e| \leq |T_e| \leq |T_{\text{ref}}| + |\Delta T_e|$: Torque should remain unchanged

3.4.2 Flux hysteresis controller

The hysteresis regulator of flux is a 2 level controller. There are 2 digital outputs for flux control loop. The flux hysteresis controller is given the stator flux error $\Delta\psi_s$ and the outcome is flux error status ($d\psi_s$) that can have two values 0 and 1. The hysteresis band width is $2\Delta\psi_s$. The switching table is given the flux error status for voltage vector optimum chosen for the inverter.

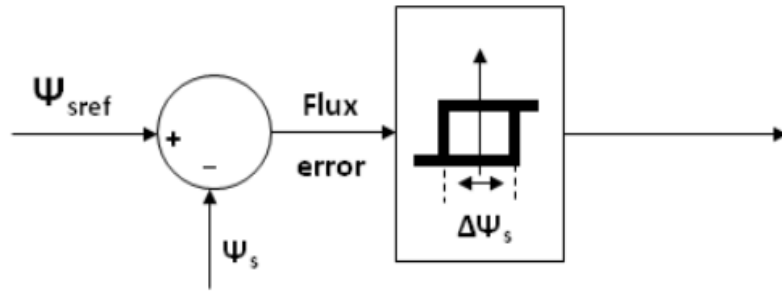


Fig.3.6 (b) Flux hysteresis

Controller error of stator flux $\Delta\psi_s = \psi_{sref} - \psi_s$

The flux is contained conording to the following mathematical equations :

$|d\psi_s| = 1$ if $|\psi_s| \leq |\psi_{sref}| - |\Delta\psi_s|$: flux should be increased

$|d\psi_s| = 0$ if $|\psi_s| \geq |\psi_{sref}| + |\Delta\psi_s|$: flux should be decreased

3.5 Conclusion

This chapter incorporated the subtle element explanation of the traditional DTC methodology. This direct torque control methodology has many merits over field arranged regulation which is examined in this part additionally has a few demerits such as generation of torque and flux ripple and changing exchanging frequency. The torque and flux ripple is because of the hysteresis regulator which can moreover be diminished fundamentally by diminishing the sampling time. The changing switching frequency is because of the part variation of the stator flux vector.

CHAPTER-4

SIMULATION MODELS, RESULTS AND DISCUSSIONS

4.1 Simulation model of IM

The three phase induction motor model is simulated by using the Matlab/Simulink. Using the set of equations provided in chapter 2, the Model is implemented. Figure 5.1 depicts the complete Simulink model of IM. The performance of the motor is first checked out for no load condition and then the load torque of 2Nm is applied and performance characteristics are drawn. The specification of the IM used is 1.5KW, 1440 rpm, 4 pole, and 3-phase with parameters: $R_s = 6.03$ ohm, $R_r = 6.085$ ohm, $L_s = L_r = 0.4893$ H, $L_m = 0.4503$ H, $J = 0.00488$ Kg.m², $B = 0.001$ Nm.sec/rad.

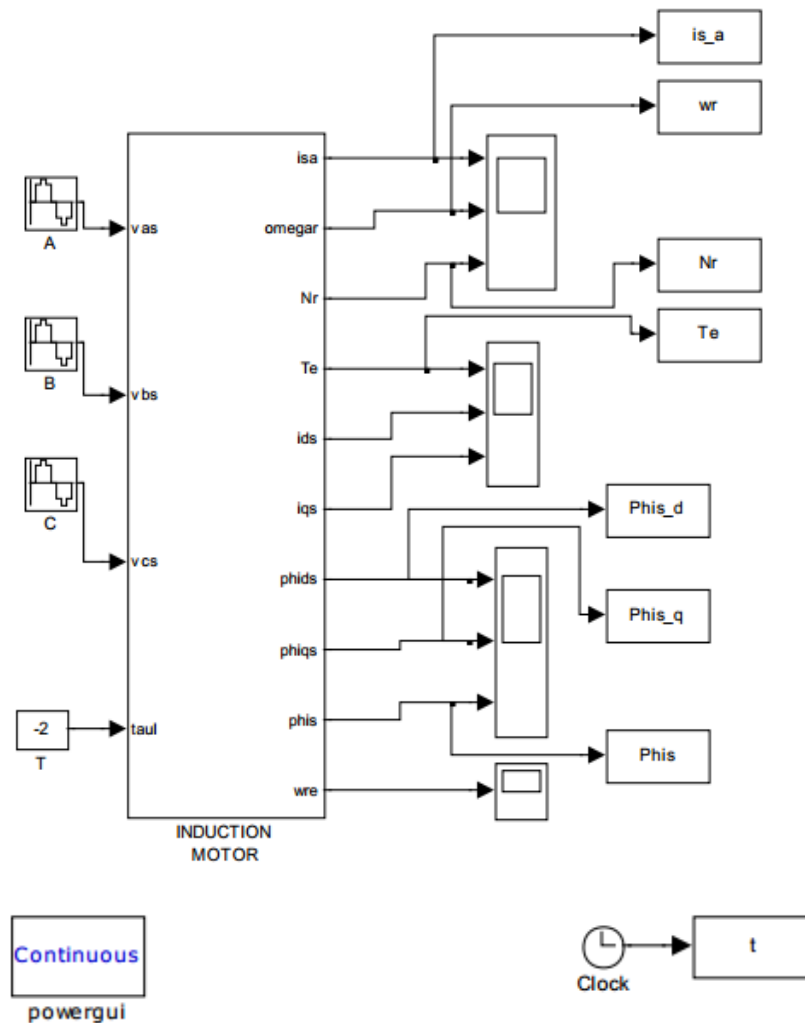


Fig.4.1 Simulation model of IM

Results for no load condition, ($T_L = 0$)

Fig.4. 2 (a) Electromagnetic torque

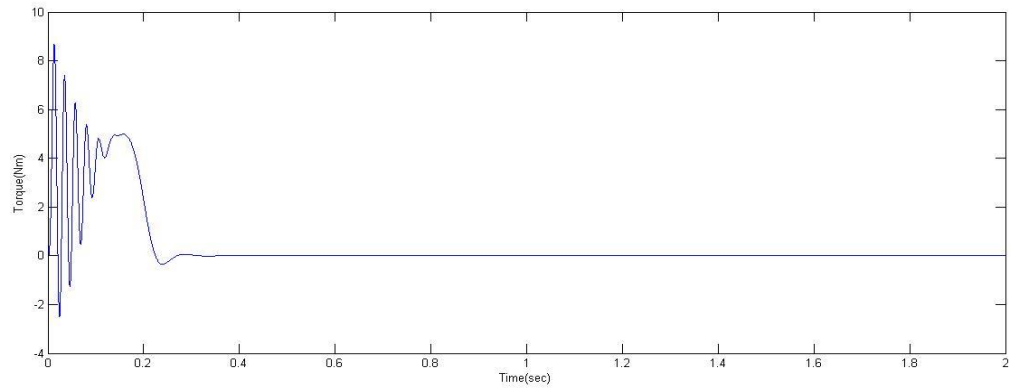


Fig. 4.2(b) Rotor speed

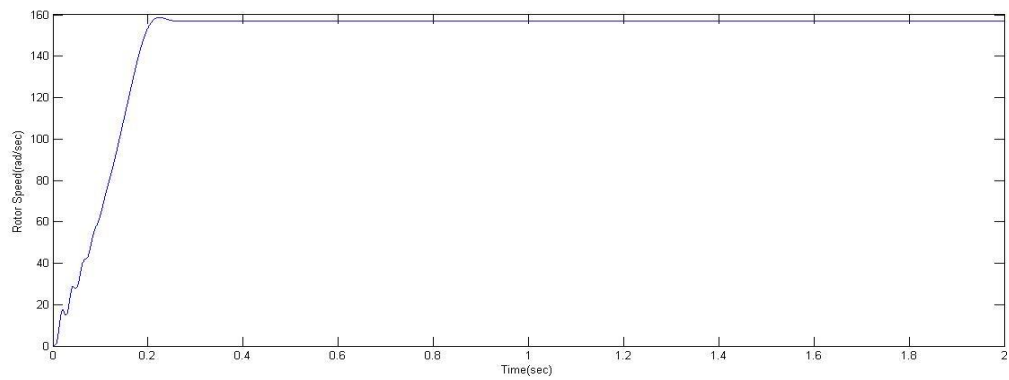


Fig. 4.2(c) Stator current

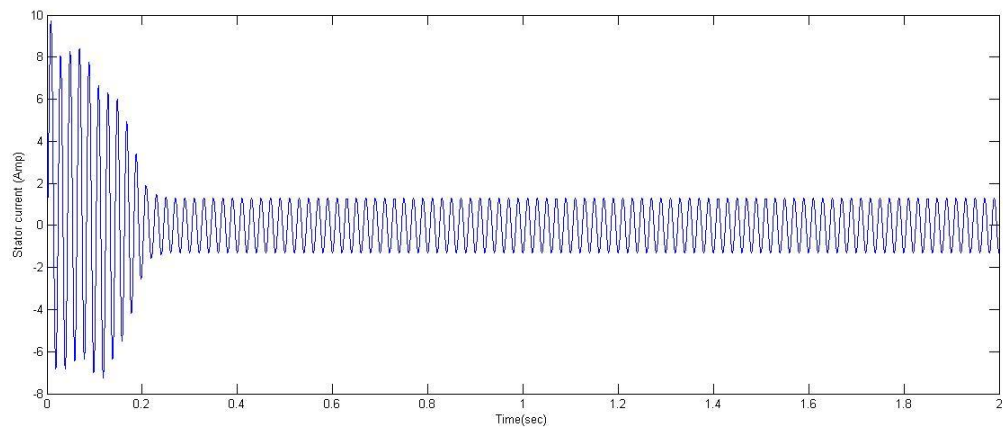


Fig.4.2 (d) d-axis stator flux

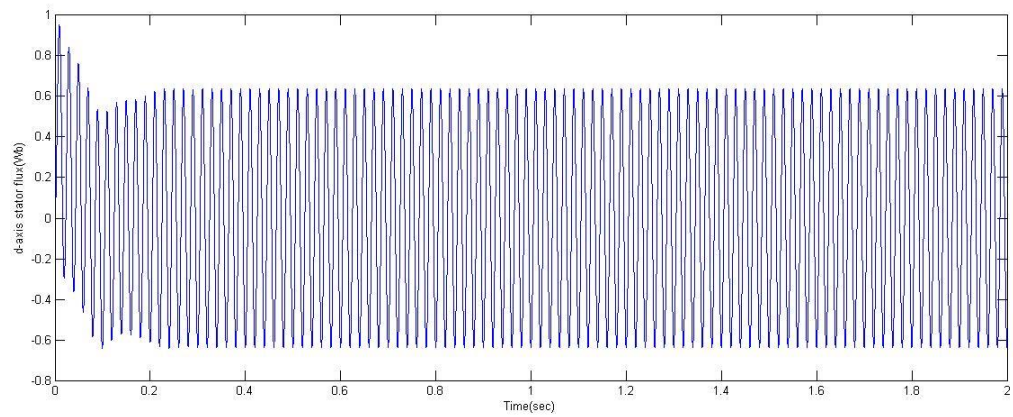
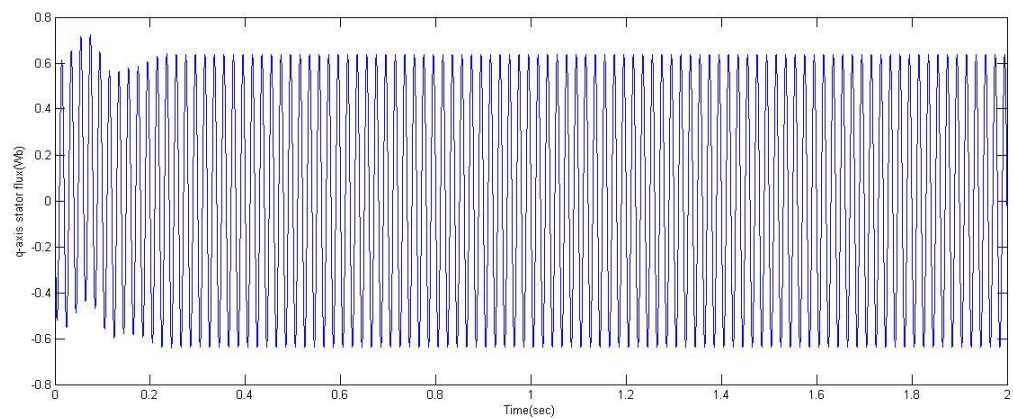


Fig.4.2 (e) q-axis stator flux



For $T_L = 2 \text{ Nm}$

Fig. 4.3 (a) Electromagnetic torque

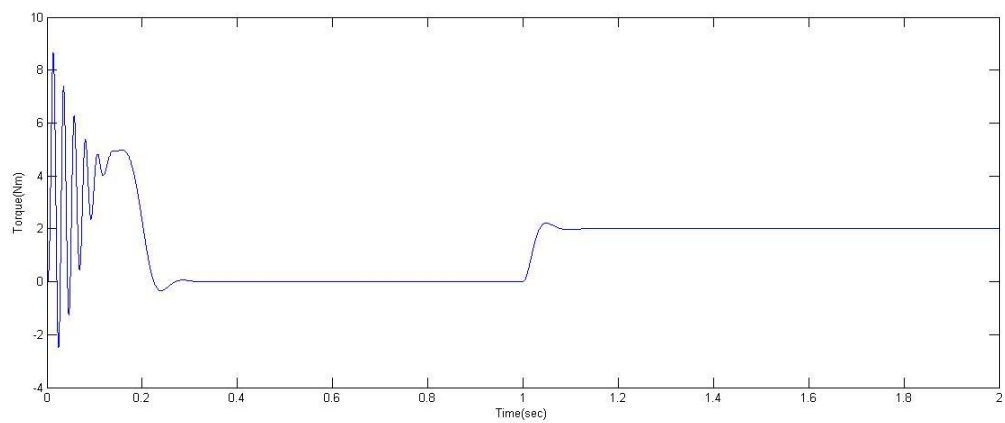


Fig.4. 3 (b) Rotor speed

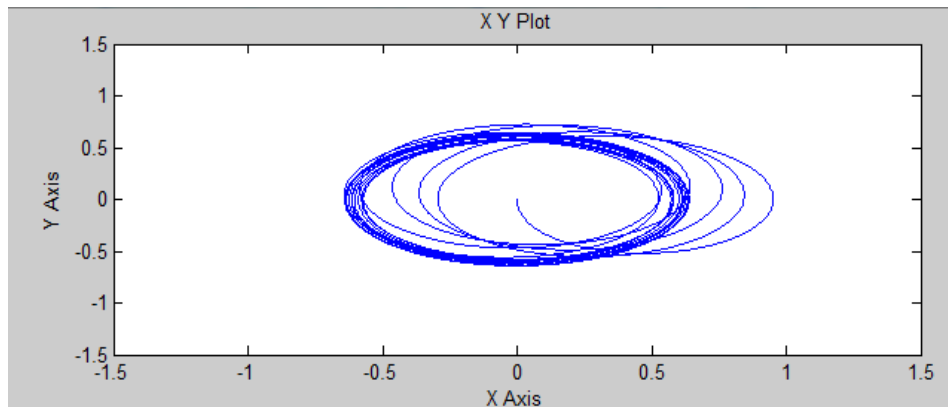
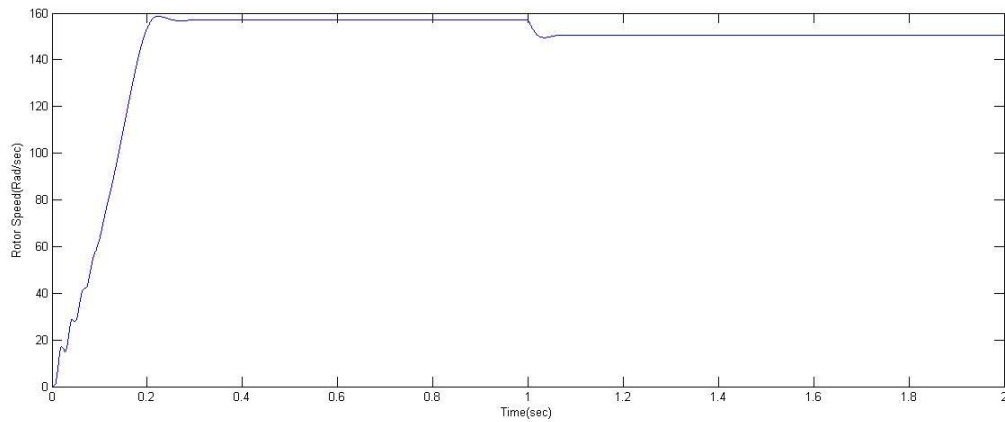


Fig.4.4 Trajectory of d axis and q axis stator flux in stationary reference frame

4.2 Simulation of DTC scheme

A DTC algorithm of IM drive has been (re-enacted) simulated using Simulink /Matlab. The reference flux linkage is taken as 1 V.s and load (burden) torque applied is 200N-m. The motor is bolstered from an IGBT PWM inverter (Universal Bridge). The SIMULINK / MATLAB model for switching rationale is produced. The transient execution of the created DTC model has been tried by applying a load(burden) torque summon on the mechanical motion(dynamics). The scheme is run for typical conditions of command speed and applied torque value. Figure 4.5 delineates the overall Simulink model of DTC scheme of IM. A 460V, 60Hz, 4pole, 200HP, 3-phase induction motor is utilized for simulation. The parameters of the IM are mentioned in appendix A.



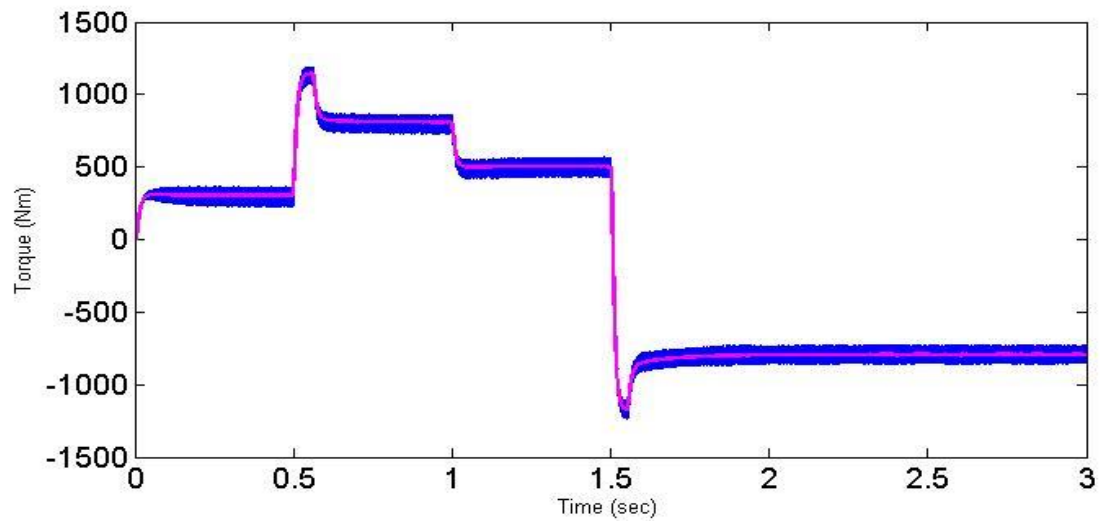


Fig.4.6 (a) Electromagnetic torque

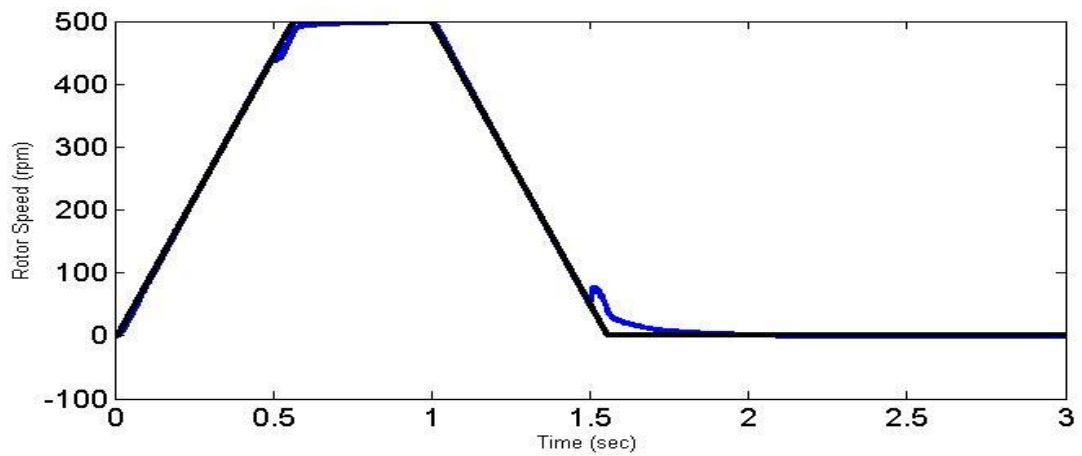


Fig. 4.6 (b) Rotor speed

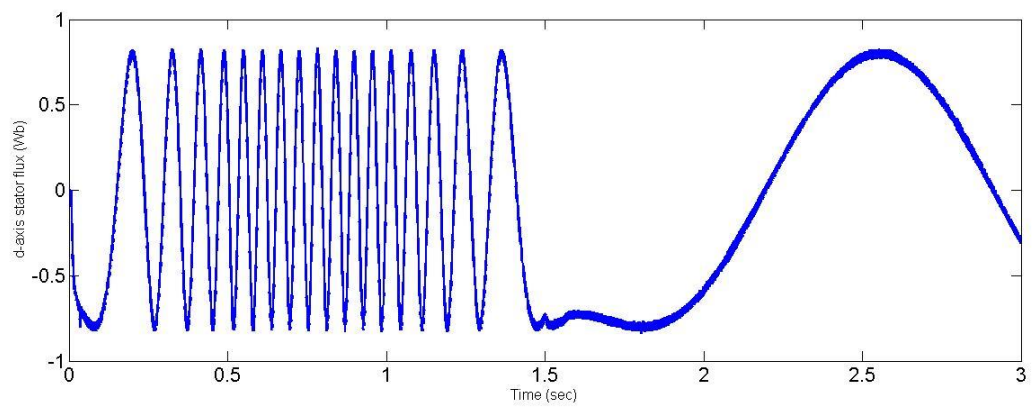


Fig. 4.6 (c) d-axis stator flux

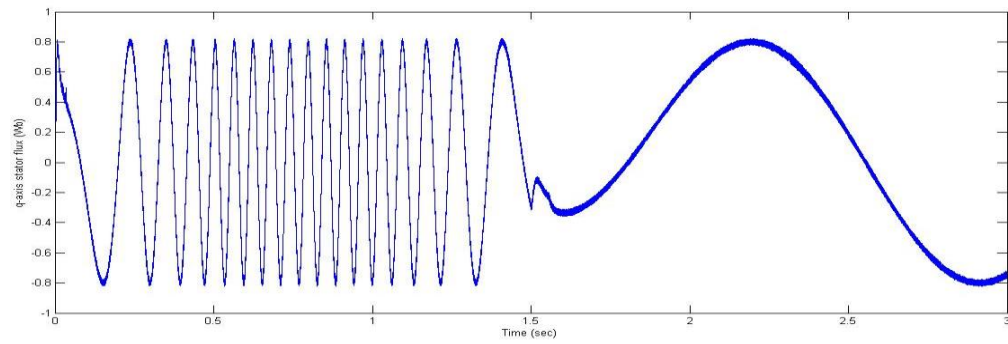


Fig.4.6 (d) q-axis stator flux

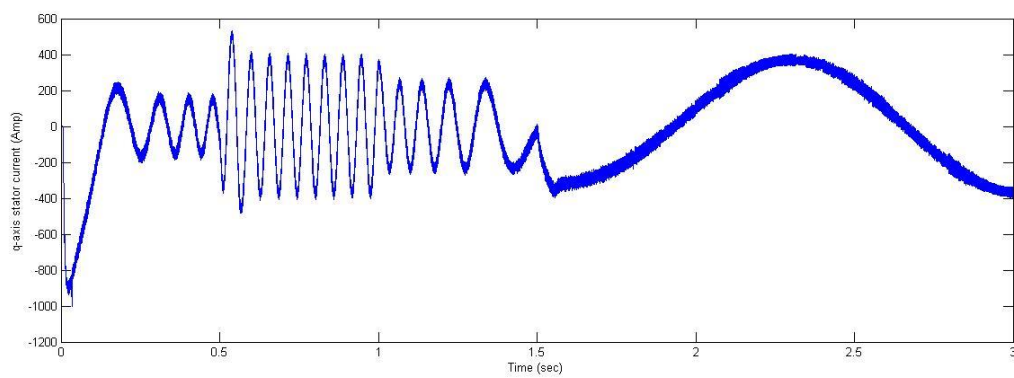


Fig 4.6(e) d-axis stator current

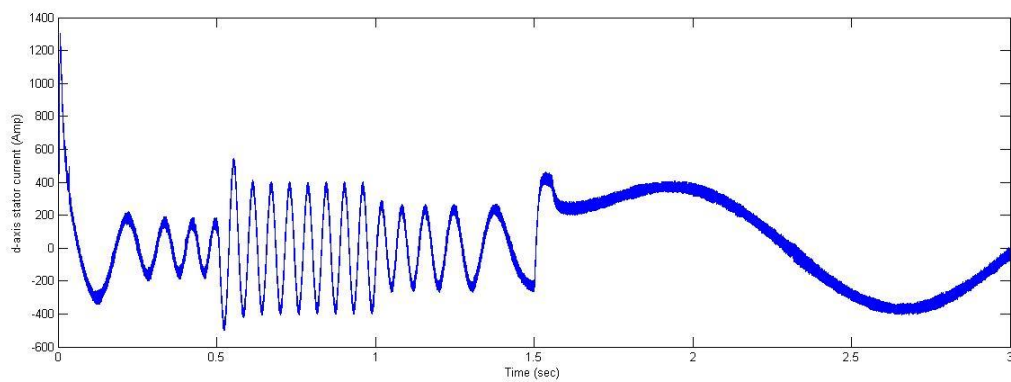


Fig.4.6 (f) q-axis stator current

CHAPTER-5

CONCLUSIONS AND FUTURE WORKS

5.1 Summary and conclusions

For any induction motor drives, DTC is one in all the best regulators suggested as such. It permits dissociated control of motor flux of stator and electromagnetic torque (T_e). From examining it is demonstrated that, this technique of induction motor control is less complex to actualize than other vector control routines as it does not oblige PWM and axes transmutations. But it presents unwanted current and torque ripple.

DTC plan utilizes stationary $d-q$ reference outline with d -axis adjusted to the stator axis. Stator voltage vector characterized in this stationary frame of reference control the flux and torque. The main conclusions from this dissertation are:

1. In transient state, by choosing the speediest accelerating vector of voltage which delivers more slip frequency, most noteworthy torsion response can be attained.
2. In steady state, the torsion can be held steady with small frequency of switching by the torque hysteresis regulator by choosing the accelerating vector and the zero voltage vector alternatively.
3. In order to attain the efficiency optimum in steady state and the noteworthy torsion response in transient state at the similar instance, the flux level could be naturally balanced.
4. If the frequency of switching is to a great degree low, the regulatory circuit makes some drift which can be balanced effectively to hinder the variation in machine parameters.

The assessment exactness of stator flux is very much needed that basically relays on resistance of stator because an error in estimation of stator flux will influence the behaviour of both flux and torque control loops. The current and torque ripple can be hindered by utilizing SVM scheme.

5.2 Future Scope of work

In traditional DTC scheme, high torque ripple is produced because the selected voltage space vector is applied for the entire switching period irrespective of the magnitude of the torque error. This torque ripple can be minimized in order to achieve a better drive functioning, by changing the duty ratio of the voltage vector selected during each switching instance, based on the magnitude of the and position of the stator flux and torsion error. This constitutes the basic of SVPWM technique. So the future work is to simulate DTC scheme based on SVPWM technique and to have comparative study of conventional DTC scheme and DTC-SVPWM scheme.

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APPENDIX-A

Open loop simulation of IM:

1.5 KW, 400V, 50Hz, 3-phase, 4 poles, 1440 rpm

$R_s = 6.03 \text{ ohm}$, $R_r = 6.085 \text{ ohm}$, $L_s = L_r = 0.4893 \text{ H}$, $L_l = 0.4751 \text{ H}$

$L_m = 0.4503 \text{ H}$, $J = 0.00488 \text{ kg.m}^2$, $B = 0.001 \text{ Nmsec/rad}$

DTC:

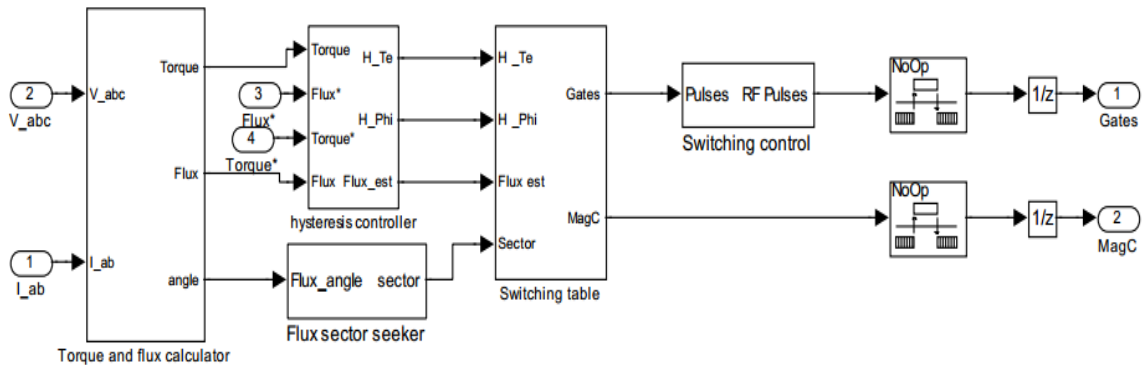
200HP, 149.2 KW, 460V, 60 Hz, 3-phase, 4 pole

$R_s = 0.01485 \text{ ohm}$, $R_r = 0.0092 \text{ ohm}$, $L_{ls} = 0.0355 \text{ H}$,

$L_{lr} = 0.0355 \text{ H}$, $L_m = 0.0104 \text{ H}$, $J = 3.1 \text{ kg.m}^2$, $B = 0.08 \text{ Nmsec}$

APPENDIX-B

(a) DTC CONTROLLER



(b) MATLAB CODING:

For sector selection:

```
function Sn = S(Ux,Uy)
theta=atan2(Uy,Ux)*180/pi; if
theta>=0&&theta<60 Sn=1;
elseif theta>=60&&theta<120 Sn=2;
elseif theta>=120&&theta<180 Sn=3;
elseif theta>=-180&&theta<-120 Sn=4;
elseif theta>=-120&&theta<-60 Sn=5;
else Sn=6; end
```